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No. 331

ATOMIZATION OF LIQUID FUELS

By Dr. R. Kuehn

PART III.

CRITICAL DISCUSSION OF EXPERIMENTAL RESULTS

MIXING THE ATOMIZED FUEL WITH AIR

From "Der Motorwagen," December 10, 1924
January 20 and February 10, 1925

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Critical Discussion of the Experimental Results

First of all, it has been established that the atomization is very uneven. This is especially noticeable at low pressures, where, indeed, most of the drops are quite large, but where there are already traces of an oil cloud, which consists of very fine drops.

If we separate the drops into three classes and designate those having a diameter of over 0.1 mm as "large," those having a diameter of less than 0.05 mm as "small" and those of intermediate diameter as "medium," we can then describe the course of the atomization, with increasing pressure, as follows: The large drops, formed at lower pressures, continually decrease in number, as the pressure increases, and finally vanish altogether at very high pressures. Conversely, the medium drops and, to a still greater degree, the small drops increase in number. The mean diameter of a large number of drops must accordingly diminish with increase in pressure. If, on the other hand, we should measure the individual

* From "Der Motorwagen," Dec. 10, 1924; Jan. 20, and Feb. 10, 1925. For Parts I and II, see N.A.C.A. Technical Memorandums Nos. 329 and 330.

drops, we would almost always find representatives of all the orders of magnitude. This is demonstrated by the experimental results. If the pressure is increased from the moment when the atomization cone first attains its full development, i.e., from about 10 kg/cm^2 to 42 kg/cm^2, the mean diameter of the gas-oil drops decreases from about 0.11 mm to 0.075 mm and of the kerosene drops from 0.08 to 0.055 mm.

The results of the individual measurements differ considerably from the above figures. They cannot be combined in a curve but only included in a zone. The size of individual drops can be either far above or far below the size of the drops in this zone. Neighboring drops in the same jet can differ several fold from one another in size. It seems as if the atomization becomes more uniform with increasing pressure. As a matter of fact, most of the large drops disappear at moderate pressures and the zone grows narrower. At higher pressures, the atomization appears to become more uniform, because the eye cannot distinguish the different sizes of the small drops clearly enough. No narrowing of the zone could, however, be confirmed experimentally (Fig. 14). The fine oil cloud, which is formed in ever increasing degree at higher pressures and which continues to hover close under the nozzle, is very much finer than the small drops in the atomization cone. Since only a portion of this cloud reaches the smoked glass and is hard to distinguish with the eye, it is probable

that, at higher pressures, the actual mean diameter is smaller than the one found by measurement. This fine cloud, however, constitutes only a negligible portion of the weight of the whole fuel jet. This may be of some importance for the combustion in an engine, as the combustion is presumably initiated or accelerated by it. The real combustion, however, which does the work in an engine, is that of the conical portion of the jet, since this contains nearly all the injected fuel. The results of our experiments apply to the conical jets. Moreover, if we are to establish any connection between the degree of atomization and the combustion defects, like backfiring, incomplete combustion, carbon deposits, etc., we must devote our attention chiefly to the largest drops in the jet. In this case, we must elevate the upper limit of the zones.

In order to discover the relation between the decrease in the size of the drops and the atomization pressure, the experimental values were plotted on a system of coordinates with logarithmic divisions. We thus obtained Fig. 24 for gas oil and Fig. 25 for kerosene.

The results of the various gas-oil experiments, with and without an atomizer rod, are included in a common zone. They demonstrate that no change in the spiral motion nor broadening of the cone, at constant atomization pressure, produces any noteworthy change in the size of the drops. This result seems to be inconsistent with the finer appearance of the broader jet.

This inconsistency is explained, however, by the fact that, for wider angles, the drops separate more and the whole jet thus becomes clearer and more transparent. Moreover, the jet, by reason of its greater width, comes into contact with a larger quantity of air, which it sets into eddying motions. Since, however, the kinematic energy of a wide jet is less, at the same atomization pressure, than that of a narrow jet (due to the fact that a portion of the pressure is absorbed in the production of the stronger spiral motion and that consequently, the discharge velocity is greatly diminished), the wide jet cannot impart so much motion to the surrounding air and the absolute velocity of the individual drops in the jet decreases much faster than in the narrow jet. The smaller drops, in particular, are soon deflected from the jet by the air in front of it and converted into a cloud which gives the jet a considerably finer appearance.

The zones for both gas oil and kerosene are plotted in Fig. 26. At the higher atomization pressures, both zones are nearly straight and parallel. In each zone there is drawn a central longitudinal line, which indicates, for each atomization pressure, the approximate mean diameter of the drops in all the experiments. These lines begin to run approximately straight in the gas-oil zone at about 20 kg/cm² and in the kerosene zone at about 7 kg/cm², i.e., after the atomization cone has assumed its final form. Above these pressures, they

can therefore be replaced by straight lines. If these lines are extended to their points of intersection with the axes of the coordinates, formulas can be written for them. These formulas show the relation between the mean drop diameter and the atomization pressure, but, of course, only for the pressure region in which the central lines of the zones are straight. Other formulas must therefore be used in the region of smaller atomization pressures. Since the zones here widen so much more rapidly with respect to the decrease in pressure, it finally becomes difficult, in the region of the lowest pressures, to find any mean drop diameter. In this region the atomization cone is still in the formative stage and the atomization begins at the bottom of a long closed oil spray. Consequently the measurements of the drops are no longer reliable, because the oil is cut by the shutter. This region, however, is of very little importance from the technical standpoint. In the region of the high atomization pressures, the validity of the formulas is established only to the limits reached in our atomization experiments. It is not improbable, however, that the central lines of the zones follow a nearly straight course even beyond these limits, at least in the adjacent region of higher pressure.

In determining the formulas for the straight lines, care must be taken to begin with 1 in the origin of the coordinates for $x = 0$ and $y = 0$ in the logarithmic diagram, since

$0 = \log 1$. Hence our diagrams receive a special scale of height by letting $d = 1$ for the drops of 0.01 mm diameter. Then the actual diameter of the drops is $D = d/100$. If, corresponding to the intersection points of the straight lines with the axes of the coordinates, we further denote by d_o the largest mean diameter of the drops at a minimum pressure $p = 1$ and p_e = the maximum pressure at the smallest mean diameter of the drops $d = 1$, we then have

$$lg\, d = lg\, d_o - \frac{lg\, d_o}{lg\, p_e}\, lg\, p \quad \text{or} \quad lg\, d = \frac{lg\, d_o}{lg\, p_e}\,[lg\, p_e - lg\, p]$$

and we obtain for both experimental liquids (due to the parallelism of the straight lines) the common equations

$$D = 0.01\,\frac{d_o}{\sqrt[3.82]{p}} \quad \text{or} \quad D = 0.01\sqrt[3.82]{\frac{p_e}{p}}$$

In both equations, d_o or p_e is apparently a function of the physical characteristics of the liquid and of the medium in which the liquid is atomized, i.e., of their viscosity, capillarity and specific gravity, as also of the shape of the nozzle. For the atomization of a given liquid in a given medium through a nozzle of a given type, we may regard the values of d_o and p_e as constant. In this case we obtain, for the relation of the diameter of the drops and the atomization pressure, $D^{3.82}p$ = a constant.

If we compare the course of the gas-oil and kerosene zones, it immediately appears that the gas-oil zone is shifted by al-

most three-fold pressure toward the right with reference to the kerosene zone, i.e., we must employ three times as much pressure for gas oil as for kerosene, in order to obtain drops of the same size. We thus obtain $p_{ker.} : p_{g.o.} = 1 : 3.05$. If, on the other hand, we compare the properties of the liquids we find that the kinematic viscosity of gas oil is also about three times as great as that of kerosene. It is $\nu_{ker.} : \nu_{g.o.} = 0.023 : 0.074 = 1 : 3.22$. We can according;y write, in this special case,

$$p_{ker.} : p_{g.o.} \sim \nu_{ker.} : \nu_{g.o.} \quad \text{or} \quad p : \nu \sim \text{constant.}$$

For p_e we obtain, after computing the constants, $p_e = 1{,}260{,}000\nu$ and correspondingly for the drop diameter

$$D = 0.4 \sqrt[3.82]{\frac{\nu}{p}}$$

If we examine this equation theoretically with respect to its qualitative correctness, we obtain, for the kinematic viscosity $\nu = \eta/\rho$, according to Reynolds law,

$$D = \text{const.} \frac{\nu}{c} = \text{const.} \frac{\nu}{\sqrt{p}} = \text{const.} \sqrt{\frac{\nu^2}{p}}$$

and, for the kinematic capillarity $k = \alpha/\rho$, *

$$D = \text{const.} \frac{k}{c^2} = \text{const.} \frac{k}{p}$$

* Surface energy = surface tension × area; hence $E = \alpha F$. If the energy of flow is contained in the surface energy, we have, when r = the radius of the drops, z the number of drops and c the velocity.

$$\frac{m\ c^2}{2} = \alpha\ F$$

$$\frac{G\ c^2}{2g} = \alpha\ z\ 4\ \pi\ r^2$$

$$\frac{4}{3}\ \pi\ r^3\ \gamma\ z\ \frac{c^2}{2\ g} = \alpha\ z\ 4\ \pi\ r^2$$

$$\frac{1}{6}\ \frac{\gamma}{g}\ r\ c^2 = \alpha$$

$$\frac{r\ \rho\ c^2}{\alpha} = \text{const. or for } k = \frac{\alpha}{\rho}$$

$$\frac{r\ c^2}{k} = \text{const.}$$

It is obvious that when the first power of p stands in the denominator, the square of ν must stand in the numerator and that the quantity k also belongs in the numerator. The latter does not come into the formula, because, in our experimental liquids, $k_{ker.} : k_{g.o.} = 32.6 : 32.8$, or almost 1. The above formula therefore applies quantitatively only to a short portion of the zones and indeed exclusively to both our experimental liquids and to our nozzle. For the following reasons also, the formula can make no claim to general applicability. It contains the quantity p as the only variable. The pressure, as measured in our experiments, cannot, however, be exclusively decisive for the degree of atomization. Since the nozzle was only borrowed and therefore could not be drilled, the pressure could only be measured at the fuel pump. Pressure is lost, however, in the pipes, in

the strainer which is located just in front of the injection valve and in the injection valve itself. A further portion of the pressure is absorbed in generating the spiral motion through the atomizer rod. Hence only a variable fraction of the measured pressure is converted into velocity at the mouth of the nozzle, as can be readily see from the course of the discharge and μ curves. For judging the size of the drops, it is therefore more important to consider its relation to the discharge velocity.

In order to plot the size of the drops against their velocity, we must first determine the absolute velocity of the jet at the mouth of the nozzle. The fuel receives a radial velocity component from the spiral motion generated by the atomizer rod. Consequently the axial velocity, as determined by measuring the discharge, is more or less below the absolute velocity, according to the pitch of the spiral. Hence the difference between the axial and absolute velocities must first be determined. The measurements of the cone angle and the discharge coefficients for the higher atomization pressures, gave the following fairly constant values:

For gas-oil

Nozzle without atomizer	3.5°	$\mu = 0.78$
" with old "	26.5	$\mu = 0.74$
" " atomizer II	43.0	$\mu = 0.54$
" " " III	49.0	$\mu = 0.51$

For kerosene

Nozzle without atomizer		4.5°	$\mu = 0.80$
" with old "		27.5	$\mu = 0.77$
" " atomizer	II	40.0	$\mu = 0.50$
" " "	III	44.0	$\mu = 0.50$

It is obvious that the spiral motion (or conical shape of the jet) considerably affects the discharge coefficients. When we consider the μ curves and compare them with the curves of the cone angles, it is especially noticeable that, at the moment when the cone attains its full development, the μ curves change, with a rather short bend, into an almost horizontal direction. The greater the angle, the more pronounced is this phenomenon. It is also worthy of note that, for atomizers II and III, which have like-pitched grooves, the same spiral motion and almost the same cone angle, the discharge coefficients μ are almost the same, although atomizer III has three grooves and atomizer II only two grooves. The total cross-sections of the grooves are therefore as 3 : 2 and the fuel velocities in the grooves as 2 : 3. The losses due to friction at this point are approximately as the squares of the velocities. Consequently the pressure losses, due to friction in the grooves of the atomizer rods, cannot be large. Since the pressure losses from friction, in the whole system of tubes from the pump to the injection valve, are equal for all the different atomizers,* the large reduction of about 30%

* See note, foot of p.11.

in μ is apparently due to the large resistance offered to the strong spiral motion of atomizers II and III in the narrow valve bore. A large portion of the pump pressure must be employed to overcome this resistance. It is remarkable that the old atomizer gives a cone angle of about 27°, whereby μ decreases by only a very small percentage. The great pressure expenditure for producing the spiral motion occurs on increasing the cone angle from about 27° to about 44°. Since the pitch of the grooves in both the new atomizers is to the pitch in the old atomizer as 1 : 2, while the tangents of the corresponding halves of the cone angle are approximately as 1 : 1.7, a larger portion of the radial velocity component is turned back by the friction in the long narrow nozzle bore into an axial direction, thereby requiring a still further expenditure of pressure. With an equally strong spiral motion, the difference in the viscosity of the liquids seems to affect the discharge coefficients but very slightly, since the corresponding values of μ for gas oil and kerosene differ but little. Still their influence on the formation of the cone seems to be of a complex nature, since the more viscous gas oil produces, with a weaker spiral motion, a somewhat narrower

(Ref. on Page 10.)
* Since no change was made in the pressure piping during the whole series of experiments, the velocities in the pipes in the experiments with atomizers II and III must be smaller, on account of the lower discharge velocities. Hence the pressure losses, due to friction in the pipes, must also be smaller than in the experiments with the old atomizer or without any atomizer.

cone, but, with a stronger spiral motion, a somewhat broader cone, than the less viscous kerosene. In the passage of the oil into and through the nozzle, the spiral motion is strongly affected by the internal friction of the oil particles among themselves and between them and the closely surrounding walls. This process and the resulting radial velocity component of the jet on leaving the nozzle can hardly be computed, due to the roughness of the inside of the nozzle, the rounding of the edges and especially the conicity of the passage into the nozzle. In the latter a hardly noticeable obstacle can produce a spiral motion, which (according to the law that the peripheral velocity × the radius is a constant) can become very strong, as is often observed in an ordinary funnel, and this spiral motion alone often suffices to produce a broad cone without any special atomizer rods. Since the effects of friction and the shape of the nozzle cannot be disregarded, it appears useless to try to compute the radial components of the discharge velocity from the pitch of the atomizer grooves. We can, however, regard the outside of the cone as the surface, into which the jet is deflected by the spiral motion. Most of the drops of the jet lie inside the surface of the cone and are but slightly deflected. We have noticed, however, that the cone is produced by the tearing of an oil spray, which is formed immediately under the nozzle and has a bulge (Fig. 21,K). Hence the spiral motion probably corresponds to a somewhat

larger cone angle than the actual one, which is diminished by the contraction of the oil spray, as a consequence of its surface tension. We will therefore assume, according to a rough estimate, that the axial discharge velocity decreases as the cosine of half the cone angle. We accordingly obtain the following absolute discharge velocities c:

For nozzle without atomizer, $c = w$;

" the old nozzle, $c = w/\cos 13.5^\circ = w/0.97$;

" nozzle II, $c = w/\cos 21^\circ = w/0.93$;

" " III, $c = w/\cos 22^\circ = w/0.92$.

Here w is the axial velocity, obtained from the discharge measurements and shown in Figs. 19 and 20.

If the diameters of the drops are plotted in a logarithmic system of coordinates, this time against c, we obtain Fig. 27 for gas oil and Fig. 28 for kerosene. In Fig. 29 the zones for both gas oil and kerosene drops are plotted. Straight lines were drawn through the zones and the formulas were worked out in the manner already described. In these formulas p_e is replaced by c_e = the maximum jet velocity (for the smallest mean drop diameter $d = 1$) and d_o = the greatest mean drop diameter at the minimum jet velocity of $c = 1$. Thus we obtain:

1. For gas oil, nozzle with old atomizer or without any atomizer,

$$D = 0.01 \frac{d_o}{\sqrt[2.21]{c}} = 0.01 \sqrt[2.21]{\frac{c_e}{c}} \quad \text{or} \quad D^{2.21}\, c = \text{const.}$$

2. For gas oil, nozzle with atomizers II and III,

$$D = 0.01 \frac{d_o}{\sqrt[2.33]{c}} = 0.01 \sqrt[2.33]{\frac{c_e}{c}} \quad \text{or} \quad D^{2.33}\ c = \text{const.}$$

3. For kerosene, nozzle with old atomizer,

$$D = 0.01 \frac{d_o}{\sqrt[2.53]{c}} = 0.01 \sqrt[2.53]{\frac{c_e}{c}} \quad \text{or} \quad D^{2.53}\ c = \text{const.}$$

From the D-c diagrams, it is first obvious that the spiral motion affects the size of the drops. At the same discharge velocity, we obtain much smaller drops with atomizers II and III than with the old atomizer or without any atomizer. In the D-p diagrams this was not manifest, because so much more pressure was required for producing the strong spiral motion and because the discharge velocity falls correspondingly so much that, for the same pump pressure, the drops have nearly the same size.

Comparison of the zones in Fig. 29, or of the above formulas, shows that d_o not only changes according to the experimental liquid and therefore depends on its physical properties, but also diminishes as the spiral motion increases and must therefore depend on the mechanical processes employed in the atomization. Similar conclusions may also apparently be drawn from the exponents of the equations. Since the exponent increases as d_o decreases, the zones in the D-w diagrams do not continue parallel, but lie the farthest apart at the smallest discharge velocities and converge as the velocity increases. We find an analogy for this converging of the zones in the for-

mation of the constrictions in the closed jet, especially with a small spiral motion, where the differences in the pressures required to produce the same shape of jet in both experimental liquids, do not increase in the same degree as the pressure. The converging of the zones leads to the conclusion that at very high discharge velocities, the diameters of the drops in both liquids will finally be approximately the same. This conclusion can be drawn, however, only with reservations. If we are to picture to ourselves the further course of the zones, beyond our experimental domain, we must first find whether the zones can actually continue to be rectilinear over a larger region. In the region of our experiments, the central lines of the zones are only approximately straight and this is true, moreover, only for the second portion of the zones. The absolute velocity c is the quotient of the axial discharge velocity of the jet w and the cosine of half the cone angle φ. The experiments show that φ remains nearly constant at the higher atomization pressures and that c approximates $w \times$ const. Between the jet velocity w and the atomization pressure p there exists the relation

$$\frac{w^2}{2g} = \mu^2 \frac{p}{\gamma}$$

As the pressure increases, the discharge coefficient μ approaches a constant final value. In the domain of our experiments and even where we have already assumed the course of the

zones to be rectilinear, μ varies quite noticeably. Consequently the diameter of the drops, if it should really change rectilinearly as a function of one or both the quantities c (or w) or p in the logarithmic system of coordinates, could not do this also as a function of one of the other quantities. Unfortunately our experimental results are yet insufficient to determine definitely whether the zones are rectilinear either in the D-p diagram or in the D-c diagram. It is possible that the zones in both cases change into curves, upward in the D-p diagram with increasing pressure and downward in the D-c diagram with increasing velocity. As a result of the bending of the zones, the exponents of the equations must also change. Hence we can conclude that even these are not only a function of the physical characteristics of the liquids, but also of the mechanical processes in the atomization and must therefore change with p or w. Even the equations in the general form, $D^n p$ or $D^n c$ = constant, are not applicable throughout the whole length of the zones, since they were likewise produced only under the assumption of the rectilinear course of the size of the drops in the logarithmic system of coordinates, while in reality the exponents, as well as the constants, are functions of the pressure (or velocity) and of the spiral motion. It is therefore obvious that the confining of our experimental results to rectilinear zones must be done with reservations and that the validity of the formulas found for these zones, in the region

where the measurements were made, must be limited for p, from about 10 to 50 kg/cm², and for c, from about 30 to 100 m/sec. But although no generally applicable law can be derived directly from our experimental results, we can nevertheless demonstrate, with respect to the physical properties of the fluids that, at the beginning of the zones and hence in the region of the minimum jet velocities, the velocities necessary to produce drops of like size with a given nozzle, are related to one another in approximately the same ratio as the viscosities of the liquids. From the convergence of the zones, we can further conclude that the effect of the viscosity on the formation of drops diminishes as the velocity increases. The effect of the surface tension appears, on the contrary, to increase constantly as the velocity of the jet increases. At very high atomization pressures, this would cause the zones of our two experimental liquids to coincide, since the difference in their capillarity is small.

Mixing the Atomized Fuel with Air

We will now consider the results of the atomization experiments with reference to the combustion requirements from the important viewpoints of atomization, distribution and penetration, as mentioned in the introduction.

The fineness of the drops is not satisfactory. Though some very fine drops are formed, especially in the cloud around

the nozzle, most of the drops in the jet exceed 0.05 mm in diameter at the pressures employed in our experiments. Consequently, in compressorless ("solid injection") Diesel engines, very high pump pressures must be employed in order to produce drops fine enough for satisfactory combustion. The ultramicroscopic investigations of Millikan demonstrate that much finer drops can be obtained than in our experiments. His finest oil drops had diameters ranging from 0.013 down to 0.0006 mm, probably about the same as for the oil drops in the above-mentioned oil cloud. Millikan's measurements were made on individual drops and cannot therefore be transferred directly to the mean diameter of the drops in the jet. We may, however, assume that the mean diameter of the drops produced by Millikan is much smaller than the values we obtained, because he used an air atomizer. With atomization by means of an air stream the drops become incomparably smaller than with solid injection, of which we can easily convince ourselves by the simple observation of experiments with the most primitive garden sprayers and which is confirmed by comparative experiments with compressorless engines and those with compressed-air injection.

Concerning the direction and distribution of the drops in the jet, much has already been said in discussing the spiral motion, the formation of the cone and its shape, so that it is not necessary to go into details here. In general, it

may be said that the distribution of the jet and its conical shape depend mainly on the shape of the nozzle and that, with our nozzle, this was not very satisfactory on account of the relatively small cone angle and especially on account of the high pressure required for increasing the cone angle. The long atomizer rods are entirely unnecessary, since the requisite spiral motion can be produced by short grooves, while the long rods only produce more friction and consequent pressure losses in the pipes.

In order to judge the distribution of the drops in the combustion chamber, we must discover how much the original velocity of the drops on leaving the nozzle is diminished by the resistance of the air. A drop encounters a resistance proportional to a function which increases with the velocity w. At low velocities, the resistance increases in proportion to the first power of the velocity and the viscosity of the air, since, according to Stokes, formula $W = 3 \pi \eta d w$. At higher velocities, the resistance increases (according to Newton's law of resistance) approximately as the square of the velocity and in proportion to the mass density of the air and the projection of the drop in its direction of motion.

$$W = \psi \frac{\gamma_L}{g} F w^2 = \psi \rho_L \frac{\pi d^2}{4} w^2$$

The coefficient is an empirically determined number, which must be a function of Reynolds number R. $\psi = f(R)$. Reynolds

number is $R = \frac{wd}{\nu}$.

We will determine the latter for the size of our drops and select, as an example, an atomization experiment with kerosene at a pressure of 42 kg/cm². The mean drop diameter $d = 0.055$ mm = 0,000055 m. The mean velocity of the jet (w) is about 80 m/sec. The kinematic viscosity of the air is

$$\nu = \frac{\eta}{\rho_L} = \frac{\eta\, g}{\gamma_L} = \frac{\eta}{\gamma_L} \quad cm^2/sec.$$

$$\eta = 0.000166 \text{ to } 0.000200 \text{ g/cm sec.}$$

γ_L (for air at 760 mm Hg and 15°C) = 0.001226 g/cm³, whence we obtain a mean of $\nu = 0.15$ cm²/sec. Hence

$$R = \frac{80 \times 0.000055 \times 100 \times 100}{0.15} \sim 300$$

This Reynolds number is extremely small. According to Prandtl's experiments on the air resistance of spheres,* a velocity of

$$w = \frac{R\,\nu}{d} = \frac{300 \times 0.15}{100 \times 100 \times 0.07} \sim 0.064 \text{ m/sec.} = 64 \text{ mm/sec.}$$

would be required (with mechanically similar processes of flow), for the smallest sphere (diameter 70 mm) tested by Prandtl. No experimental investigations of the processes of flow in the air at such low velocities have thus far been published, so that it appears doubtful as to which of the two resistance

* See "Mitteilungen aus der Göttinger Modellversuchsanstalt," No. 16, and "Der Luftwiderstand von Kugeln," C. Wieselsberger, in "Zeitschrift für Flugtechnik und Motorluftschiffahrt," 1914, p. 140.

formulas applies to the case in hand. We now know, from Lenard's experiments, that the transition to the quadratic law takes place at the final velocity of water drops having a diameter of 0.29 mm. According to Stokes' formula, this final velocity is

$$w = \frac{2}{9} \frac{g\, r^2\, s}{\eta}$$

and therefore

$$w = \frac{\gamma\ \text{water}}{18\ \eta}\, d^2$$

for

$$\eta = 0.000172\ \frac{g}{cm \times sec.}\ \text{is}\ \eta = \frac{\eta}{g} = 0.00000175\ \frac{kg \times sec.}{m^2}$$

$$w = \frac{1000 \times 0.00029^2}{18 \times 0.00000175} \sim 2.6\ m/sec.$$

for which we obtain the following Reynolds number

$$R = \frac{w\ d}{\nu} = \frac{2.6 \times 0.00029 \times 100 \times 100}{0.15} \sim 50$$

For our atomization drops of 0.000055 m diameter, we would therefore obtain the following velocity as the upper limit for the applicability of Stokes' formula,

$$w = \frac{R\ \nu}{d} = \frac{50 \times 0.15}{0.000055 \times 100 \times 100} \sim 13.6\ m/sec.$$

Our discharge velocities are much greater, so that the quadratic resistance law applies. It is only after the drops have lost the larger part of their initial velocity that Stokes' law can be applied to them. At the velocity limit of 13.6 m/sec., the resistance computed by one formula must be nearly the same

as when computed by the other formula. We can therefore employ the following equation

$$3 \pi \eta d w = \psi \rho_L \frac{\pi d^2}{4} w^2$$

from which we obtain

$$\psi = \frac{12\eta}{\rho_L d w} = \frac{12\nu}{d w} = \frac{12}{R}$$

Since we have already obtained the Reynolds number $R = 50$ for the velocity limit, we have $\psi = \frac{12}{50} = 0.24$. This value agrees exactly with the resistance figures found by Prandtl in his Göttingen experiments with spheres and we will therefore use it in our further calculations. On comparing ψ with Lenard's value $A = 0.153$ (See Part I, Technical Memorandum No. 329), we have

$$\psi = \frac{4}{3} A = \frac{4}{3} \times 0.153 = 0.204.$$

Starting with atomization pressures of different magnitudes, we will now determine the velocities and distances traversed by the drops (for their correspondingly determined diameters and initial velocities) with relation to the time elapsed. In order to obtain a comprehensive picture, we will distribute the selected atomization pressures over a region extending up to 1000 kg/cm². We will have to take the corresponding drop diameters, in so far as they do not lie within the field of our experimental results, from the plotted atomization zones and likewise compute the corresponding initial velocities with

the aid of extrapolated μ curves. We need have no fear that the extrapolated values may not correspond to reality, because, as we shall see later, that would make very little difference with the results of the computation and none at all with the conclusions which can be drawn. The computation will be made for two different cases: atomization in the open air, as in our experiments, and atomization in a Diesel engine.

We do not yet know how much the degree of atomization changes in the highly compressed air in the engine. However, on account of the great importance of this case, we will make the computation on the assumption that the size of the drops remains the same as in the open air. We shall see later that even this assumption can in no way impair the final result of the computation.

For the Diesel engine, we will take the normal case in which air at atmospheric tension and about 110°C initial temperature in the cylinder is compressed to about 32 atmospheres additional pressure. The chosen atomization pressures will then be greater than the compression tension and will therefore be designated in the computation tables as pressure differences. Kerosene will be the atomization liquid. We will divide the time into very short intervals to correspond to the very rapid course of the combustion processes in a Diesel engine.

The acceleration force of a drop is $P = m\frac{dw}{dt}$ and its

mass is $m = \frac{\pi d^3}{6} \frac{\gamma_P}{g} = \frac{\pi d^3}{6} \rho_P$. The force must now equal the resistance, i.e.

$$P = - W$$

$$\frac{\pi d^3}{6} \rho_P \frac{dw}{dt} = - \psi \rho_L = \frac{\pi d^2}{4} w^2$$

whence it follows that

$$\frac{dw}{dt} = - \frac{1.5 \psi \rho_L}{d \rho_P} w^2$$

We will now put $\frac{1.5 \psi \rho_L}{d \rho_P} = \frac{1.5 \psi \gamma_L}{d \gamma_P} = k$ and will next determine this constant for each drop diameter in both computation cases.

Table III.

Velocity and distance traversed by a drop after passing from the nozzle into air under atmospheric pressure.

Pressure difference p kg/cm²		10	20	50	100	200
Drop diameter d mm		0.081	0.067	0.053	0.044	0.037
Theoretical discharge velocity w_{th} m/sec.		49.2	69.5	110	155	220
μ		0.660	0.735	0.770	0.785	0.795
Discharge velocity w_o m/sec.		32.5	51.0	84.0	121.7	175
k 1/m $k = \frac{.545}{d}$		6.7	8.0	10.2	12.2	14.6
	Time τ sec.					
Velocity w m/sec. $w = \frac{w_o}{1 + w_o kt}$	0.00002	33.4	50.6	83.4	118.0	166.0
	0.00005	32.2	50.0	81.2	113.0	155.0
	0.0001	31.8	49.0	78.0	106.0	139.0
	0.0002	31.1	47.1	72.2	94.0	116.0
	0.0005	29.3	42.5	59.3	70.0	77.0
	0.001	26.6	36.2	45.4	49.0	49.2
	0.002	22.6	28.0	31.0	30.7	28.6
	0.005	15.5	16.8	15.9	14.5	17.7
	0.01	10.2	10.0	8.8	7.7	6.6
	0.02	6.1	5.6	4.6	4.0	3.35
Distance traversed s m $s=\frac{1}{k}\log(1+w_o kt)$	0.00002	0.00059	0.00099	0.00165	0.00242	0.0033
	0.00005	0.00164	0.00249	0.00413	0.00585	0.0083
	0.0001	0.00325	0.00502	0.0081	0.0113	0.0156
	0.0002	0.00643	0.00985	0.0156	0.0213	0.0283
	0.0005	0.0156	0.0238	0.0350	0.0454	0.0564
	0.001	0.0297	0.0429	0.0608	0.0744	0.0870
	0.002	0.0545	0.0748	0.0987	0.113	0.124
	0.005	0.101	0.139	0.164	0.175	0.180
	0.01	0.173	0.203	0.222	0.226	0.224
	0.02	0.250	0.277	0.285	0.280	0.270

Table III (Cont.

Velocity and distance traversed by a drop after passing from the nozzle into air under atmospheric pressure.

Pressure difference p kg/cm^2		400	600	800	1000
Drop diameter d mm		0.031	0.028	0.026	0.024
Theoretical discharge velocity w_{th} m/sec.		311	381	440	492
μ		0.805	0.810	0.812	0.814
Discharge velocity w_o m/sec.		250	308	357	400
k 1/m $k = \frac{.545}{d}$		17.6	19.5	21.1	22.5
	Time τ sec.				
Velocity w m/sec. $w = \frac{w_o}{1 + w_o\ kt}$	0.00002	230	275	310	393
	0.00005	205	237	258	276
	0.0001	174	192	204	210
	0.0002	133	140	143	143
	0.0005	78	77	75.2	72.8
	0.001	46.3	44	42.0	40.0
	0.002	25.5	23.7	22.3	21.0
	0.005	10.9	10.0	9.2	8.7
	0.01	5.6	5.05	4.5	4.4
	0.02	2.8	2.54	2.36	2.2
Distance traversed s m $s = \frac{1}{k} \log(1+w_o\ kt)$	0.00002	0.0048	0.0058	0.0066	0.0074
	0.00005	0.0113	0.0134	0.0152	0.0165
	0.0001	0.0207	0.0241	0.0265	0.0285
	0.0002	0.0358	0.0404	0.0434	0.0458
	0.0005	0.0660	0.0711	0.0742	0.0756
	0.001	0.0959	0.1000	0.101	0.102
	0.002	0.1295	0.1315	0.131	0.130
	0.005	0.178	0.176	0.173	0.170
	0.01	0.216	0.211	0.205	0.200
	0.02	0.255	0.246	0.238	0.231

Table IV.

Velocity and distance traversed by a drop after passing from the nozzle into air under 32 atm. additional pressure.

Pressure difference p kg/cm²		10	20	50	100	200
Drop diameter d mm		0.081	0.067	0.053	0.044	0.037
Theoretical discharge velocity w_{th} m/sec.		49.2	69.5	110	155	220
μ		0.660	0.735	0.770	0.785	0,795
Discharge velocity w_o m/sec.		32.5	51.0	84.0	121.7	175
k 1/m $k = \frac{.545}{d}$		99	120	150	182	220
	Time τ sec.					
Velocity w m/sec. $w = \frac{w_o}{1 + w_o kt}$	0.00002	30.5	45.5	67.5	84.4	99
	0.00005	28.0	39.1	51.8	57.7	60
	0.0001	24.6	31.6	37.3	37.8	36.1
	0.0002	19.7	23.0	23.9	22.4	20.1
	0.0005	12.5	12.6	11.5	10.0	8.8
	0.001	7.7	7.2	6.2	5.2	4.4
	0.002	4.4	3.9	3.2	2.7	2.2
	0.005	1.9	1.6	1.3	1.1	0.9
	0.01	1.0	0.82	0.66	0.52	0.45
Distance traversed s m $s=\frac{1}{k}\log(1+w_o kt)$	0.00002	0.00063	0.00096	0.00151	0.00202	0.00259
	0.00005	0.00151	0.00222	0.00327	0.00411	0.00487
	0.0001	0.00282	0.00398	0.00546	0.00644	0.00718
	0.0002	0.00503	0.00664	0.00844	0.00931	0.00983
	0.0005	0.0097	0.0117	0.0133	0.0137	0.0136
	0.001	0.0145	0.0163	0.0174	0.0173	0.0171
	0.002	0.0202	0.0215	0.0218	0.0209	0.0198
	0.005	0.0287	0.0288	0.0278	0.0259	0.0239
	0.01	0.0354	0.0344	0.0324	0.0297	0.0270

Table IV (Cont.)

Velocity and distance traversed by a drop after passing from the nozzle into air under 32 atm. additional pressure.

Pressure difference p kg/cm²		400	600	800	1000
Drop diameter d mm		0.031	0.028	0.026	0.024
Theoretical discharge velocity w_{th} m/sec.		311	381	440	492
μ		0.805	810	0.812	0,814
Discharge velocity w_o m/sec.		250	308	357	400
k 1/m $k = \frac{.545}{d}$		260	290	312	330
	Time τ sec.				
Velocity w m/sec.	0.00002	109	111	110	110
	0.00005	58.9	56.4	54.1	52.6
	0.0001	33.4	31.0	29.2	28.2
	0.0002	17.9	16.4	15.2	14.6
	0.0005	7.5	6.8	6.3	6.0
	0.001	3.8	3.4	3.16	3.0
	0.002	1.9	1.7	1.58	1.51
$w = \frac{w_o}{1 + w_o kt}$	0.005	0.77	0.69	0.64	0.60
	0.01	0.38	0.34	0.32	0.30
Distance traversed s m	0.00002	0.00320	0.00353	0.00377	0.00392
	0.00005	0.00557	0.00586	0.00605	0.00616
	0.0001	0.00775	0.00792	0.00802	0.00804
	0.0002	0.01014	0.0101	0.01009	0.01002
	0.0005	0.0135	0.0132	0.0129	0.0127
	0.001	0.0161	0.0155	0.0151	0.0148
	0.002	0.0187	0.0179	0.0174	0.0169
	0.005	0.0222	0.0210	0.0203	0.0197
$s=\frac{1}{k}\log(1+w_o kt)$	0.01	0.0249	0.0234	0.0225	0.0218

In both cases we have approximately

$$\gamma_P \text{ (kerosene at } 18.6^\circ\text{C)} = 0.812 \times 1000 = 812 \text{ kg/cm}^3$$

$$\rho_P = \frac{812}{9.91} = 82.6 \frac{\text{kg} \times \text{sec.}^2}{\text{m}^4}$$

1. Atomization in open air.

$$\gamma_L \text{ (air at 760 mm Hg and } 15^\circ\text{C)} = 0.001226 \text{ g/cm}^3$$

$$\rho_L = \frac{1.226}{9.81} = \frac{1}{8} \frac{\text{kg} \times \text{sec.}^2}{\text{m}^4}$$

2. Atomization in engine.

For polytropic compression, we have

$$\frac{\gamma_2}{\gamma_1} = \left(\frac{p_2}{p_1}\right)^{\frac{1}{n}} \quad \text{and} \quad \frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}$$

Then $p_1 = 1$; $p_2 = 33$; $n = 1.3$; $T_1 = 383^\circ$; $\gamma_2 = 18$ kg/m³ and $T_2 = 858^\circ$. $\rho_2 = \frac{18}{9.81} = 1.84 \frac{\text{kg} \times \text{sec.}^2}{\text{m}^4}$

We then have for k:

In open air,

$$k_L = \frac{1.5 \times 0.24 \times 1000}{8 \times 82.6\ d} \left[\frac{1}{m} \text{ for d in mm}\right]$$

$$k_L = \frac{0.545}{d}$$

In engine,

$$k_M = \frac{1.5 \times 0.24 \times 1000 \times 1.84}{82.6\ d} \left[\frac{1}{m} \text{ for d in mm}\right]$$

$$k_M = \frac{8}{d}$$

After determining the constants for both computation cases,

by dividing by the individual drop diameters, we again continue our first computation.

$$\frac{dw}{dt} = - k w^2$$

$$\frac{dw}{w^2} = - k\, dt \qquad \int_{w_o}^{w} \frac{dw}{w^2} = - k \int_o^t dt$$

$$\frac{1}{w} - \frac{1}{w_o} = kt \qquad \frac{1}{w} = \frac{1 + w_o kt}{w_o}$$

$$w = \frac{w_o}{1 + w_o kt}$$

If we designate the distance traversed by s, we have

$$w = \frac{ds}{dt} \quad \text{hence} \quad d\,s = \frac{w_o\, dt}{1 + w_o kt}$$

$$\int_o^s d\,s = \int_o^t \frac{w_o\, d\,t}{1 + w_o kt}$$

$$s = \frac{1}{k}\; ln\,(1 + w_o\, k\, t)$$

The velocities and distances, computed according to the above formulas, are given in the accompanying tables, both for atomization in the open air (Table III) and in an engine (Table IV). In order to make the computed results still clearer, they are plotted in Figs 30-31 against the time and the atomization pressure.

The computation shows that the velocity of a drop diminishes very rapidly with reference to the time and that, therefore, the distance traversed almost completely ceases to in-

crease after a few thousandths of a second.

As an example suited to the operating conditions of a compressorless Diesel engine, we will consider the behavior of a drop which has a diameter of 0.03 mm and is driven by a pump pressure of 432 atm., with an initial velocity of 250 m/sec., into a compression chamber full of air under 32 atm. above normal atmospheric pressure. After 0.0001 second its velocity is only about 30 m/sec. and the distance traversed is only about 8 mm. After 0.001 sec. the velocity has fallen to about 4 m/sec. (Here Stokes' law must already apply) and the distance has increased to 16 mm. After 0.01 sec. the velocity has fallen to only 0.4 m/sec. (practically 0) and the distance traversed has about reached its upper limit. In the meantime, however, the combustion process must have been completed.

Whether the drops are a little larger or smaller does not affect the gist of the matter. For the case in the engine, the most we can assume is that the drops, produced by injection into the compressed air, are, on account of the greater air resistance, smaller than in the open air. If they should be very much smaller, our computation would give very crude results.

The smaller the drops, the faster they lose their velocity. Even if, with increasing pressure, the smaller drops, on account of their initial velocity, traverse a longer distance in the first moment, this distance approaches its upper limit all the more rapidly and the larger drops, which are produced at a

lower pressure and therefore have a lower initial velocity, very soon overtake the smaller drops. We therefore obtain, for a given time interval with increasing atomization pressure and consequent decreasing size of drops, first an increase in velocity and distance and then a decrease in both. The limit is indicated in the tables by a heavy dividing line. As the time increases, the limit is shifted farther into the region of smaller atomization pressures. This means that in order to go the farthest, a drop must be larger in proportion to the time allowed it to traverse the distance. The maxima are so inconspicuous in the plotted diagrams that they can hardly be distinguished.

In the open air, the distance traversed by a drop is counted in centimeters and in the engine only in millimeters. We can, therefore, sum up the result of our computation in a sentence: In the short time required for the combustion, a single drop does not have the power to penetrate the air any appreciable distance.

That the drops do, nevertheless, penetrate the space, is due to the whole jet, which imparts to the surrounding air a whirling motion, which carries the individual drops along with it. The total kinematic energy of all the drops is therefore transmitted to the air. The air is not given a stationary whirling motion, but a flow in the direction of the jet. Its velocity is accelerated by the drops, while the velocity of

the drops themselves is diminished. The drops are thus, in fact, soon brought to a standstill in relation to the air, but the task of distributing the drops in space has been transferred to the surrounding air. This phenomenon was beautifully shown in the water-filled glass balloon, since the density of the water was about 56 times as great as the density of the air compressed at 32 atm. and the motions were correspondingly slow.

If we have a jet in the form of the surface of a cone, then the surrounding air, at least in so far as the drops are fairly contiguous, attains almost the same velocity as the jet, while the air inside the cone forms eddies and likewise flows back on the outside with the formation of eddies. The finest drops are the most easily deflected by the air eddies outward or inward from the hollow cone. We can therefore understand how a fine oil cloud is formed outside the cone, especially at high atomization pressures, and is carried upward in shreds. The experiments in catching the drops on a pad always showed that the smallest drops were in the center and on the periphery of the atomization pattern. When, on observing a jet in the open air, such a small drop flies from the side of the cone it is seen to describe a very short curve and immediately lose its velocity and perhaps even be carried upward by the air.

Even when the jet has just left the nozzle, its velocity with relation to the air (so long as the jet is continuous)

is small in comparison with its absolute velocity in space, since the air from above flows down along the nozzle in the direction of the jet. Consequently, we must assume that the resistance of the air can exert but a relatively small influence on the formation of the drops.

The transfer of the energy from the jet to the air is accomplished all the more completely, the closer the surface of the jet is exposed to the air. It is therefore useless to tear the jet apart by a very strong spiral motion with the object of distributing the drops as much as possible in the combustion chamber, for the broader the cone, the greater is the mass of air it must set in motion and, therefore, the smaller the velocities (for jets of equal strength) which will be imparted to the air currents. For this reason, as demonstrated by Hawkes, Chaloner, Hesselmann and others, nozzles with single smooth bores, without any artificially produced spiral motion, and giving only a moderately broad conical jet, have proved to be the best in practice, especially for large engines. On the other hand, it is possible to so adapt the shape of the combustion chamber, that the air will flow in certain directions along its walls and thus effect the most thorough distribution of the fuel in the chamber.

From the above, it follows that, along with the fineness of the drops, the most important condition for perfect combustion is the suitable circulation of the air. This is also demonstrated by the good results recently obtained with engines

having a specially shaped piston for setting up eddies in the combustion chamber, and likewise with engines in which the energy resulting from a preliminary partial explosion is utilized to drive the fuel into the combustion chamber, while simultaneously setting up eddies in the air.

In conclusion, let us briefly compare a "solid-injection" engine with an "air-injection" engine, with reference to the production of air eddies by the energy of the jet. The energy of a jet, as it leaves the nozzle, is given by the expression $\frac{MW^2}{2}$. In the "air-injection" method there is, in addition to the fuel charge, an almost equal mass of compressed air which receives through its expansion a very high exit velocity which, in turn, is also imparted to the oil drops enclosed in the compressed air. In order to produce an equally great energy of flow by "solid injection," an extremely high pump pressure would have to be employed.* It is, therefore, obvious that

* Neumann, "Untersuchungen an der Diesel-maschine" Z.d.V.d.I., 1923, p. 755.
For a 50 HP. engine under full load and $n = 216$ R.P.M., in a working test, the load was found to be:
Gas oil ($\gamma = 0.878$) = 0.00165 kg;
Injection air (15°C, 1 atm.) = 0.001228 m³ = 0.00146 kg.
The discharge velocity (w), with adiabatic expansion, under an "air-injection" pressure of 61 atm. (50°C) against a compression pressure of 35 atm., is 306 m/sec. The energy of flow is

$$E = G_{air} + G_{fuel}) \frac{w^2}{2g} = 14.8 \text{ m/kg}$$

The production of the same energy by pressure atomization ("solid injection") requires:

$$w = \sqrt{\frac{14.8 \times 2 \times 9.81}{0.00165}} = \sqrt{17600} = 419 \text{ m/sec.}$$

$$p = \frac{w^2}{\mu^2}\frac{\gamma}{2g} \quad \text{and on the assumption that} \quad \mu = 0.8 \text{ is}$$

(Continued at foot of next page)

the "air-injection" method is vastly superior to "solid injection" for producing turbulence in the air.

The different jet forms, described in Part II, Technical Memorandum No. 330, lead to the conclusion that neighboring liquid particles in the jet have velocities of different magnitude and direction. Even in the orifice of the nozzle, differences in velocity are produced by the retardation, through friction, of the particles next to the wall. These particles, in turn, retard the neighboring particles toward the center of the jet. Hence the velocity is highest in the middle of the jet and diminishes toward the outside. The different directions of the liquid particles are due to the shape of the walls between which they flow and to the spiral motion of the jet.

After the liquid particles have left the nozzle with a certain velocity and direction, they move freely through the air and set it likewise in motion. All the particles, both of the liquid and of the air, have, at every point, a force K_T corresponding to their mass m and their acceleration b. Hence $K_T = m\ b$.

The resulting acceleration force is determined by the following forces:

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*(Continued from Page 35)

$$p = \frac{17600 \times 0.878}{0.64 \times 2 \times 9.81 \times 10} = 1230 \text{ kg/cm}^2$$

Hence the injection must be about twenty times as large.

1. The force of gravity K_s, found by multiplying the mass m by the acceleration due to gravity g. Hence $K_s = mg$. If, under the influence of gravity, the processes of flow take place in accordance with the law of mechanical similitude, we have, according to Froude, $c/\sqrt{l} = \text{const.}$* If the corresponding velocities, distances and times are designated by c_1 c_2, l_1 l_2, t_1 t_2, the following relations exist between their ratios:

$$\frac{c_1}{c_2} = \sqrt{\frac{l_1}{l_2}} \qquad \frac{l_1}{l_2} = \frac{t_1^2}{t_2^2} \qquad \frac{t_1}{t_2} = \sqrt{\frac{l_1}{l_2}}$$

2. The forces of friction K_R, due to the viscosity of the liquid and of the air. If the coefficient of friction is designated by η and if $\delta c/\delta u$ denotes the velocity variations δc, while advancing a distance δu in the vertical direction on the friction surface, then the molecular or adhesive tension, produced on the area F by the viscosity of the liquid and of the air, is $\eta \frac{\delta c}{\delta u}$, whence we obtain $K_R = \eta \frac{\delta c}{\delta u} F$, as the force of friction.

In mechanically similar processes, the Reynolds law applies to the liquid friction and, if we designate the mass density of the liquid by $\rho = \gamma/g$ and its kinematic viscosity by $\nu = \eta/\rho$, we obtain $cl/\nu = \text{const.}$ The following relations then exist between the ratios of the velocities, distances and times:

$$\frac{c_1}{c_2} = \frac{\nu_1 l_2}{\nu_2 l_1} \qquad \frac{l_1}{l_2} = \sqrt{\frac{\nu_1 t_1}{\nu_2 t_2}} \qquad \frac{t_1}{t_2} = \frac{\nu_2 l_1^2}{\nu_1 l_2^2}$$

*Weber, "Die Grundlagen der Achnlichkeitsmechanik und ihre Verwertung," Jahrbuch der Schiffbautechnischen Gesellschaft, 1919.

3. The capillary forces due to the surface tension of the liquid. The tension in the top layer of a liquid α (capillary constant) is due to a capillary force K_k, which acts along a unit distance on the surface. Hence $K_\kappa = \alpha l$. In analogy with the Reynolds law, a corresponding law can be derived for mechanically similar processes due only to the effect of capillary forces. If we again designate the mass density of the liquid by $\rho = \gamma/g$ and its kinematic capillarity by $\kappa = \alpha/\rho$, we obtain $\frac{c^2 l}{\kappa}$ = const. For the relations between the velocities, distances and times, we then have

$$\frac{c_1}{c_2} = \sqrt{\frac{\kappa_1}{\kappa_2}\frac{l_2}{l_1}} \qquad \frac{l_1}{l_2} = \sqrt[3]{\frac{\kappa_1}{\kappa_2}\frac{t_1^2}{t_2^2}} \qquad \frac{t_1}{t_2} = \sqrt{\frac{\kappa_2}{\kappa_1}\frac{l_1^3}{l_2^3}}$$

In order to determine the simultaneous effect of the viscosity and capillary forces for mechanically similar processes, the following conditions, derived from the above formulas, must be fulfilled: $c\,\nu/\kappa$ = const.; also $c\,\eta/\alpha$ = const. For the velocities, distances and times, we then have

$$\frac{c_1}{c_2} = \frac{\nu_2}{\nu_1}\frac{\kappa_1}{\kappa_2} \qquad \frac{l_1}{l_2} = \frac{\nu_1^2}{\nu_2^2}\frac{\kappa_2}{\kappa_1} \qquad \frac{t_1}{t_2} = \frac{\nu_1^3}{\nu_2^3}\frac{\kappa_2^2}{\kappa_1^2}$$

While, in the separate consideration of the effects of gravity, viscosity and capillarity for mechanically similar processes, the choice of the ratio of one of the three quantities, c, l, and t, remains open, neither of the ratios is optional for the mutual effect of viscosity and capillarity, but they are all determined by the physical properties of the liquids compared.

If gas oil is designated by the index 1 and kerosene by the index 2, we obtain, for our two experimental liquids,

$$c_1 : c_2 = 1 : 3.2 \qquad l_1 : l_2 = 10.3 \qquad t_1 : t_2 = 33$$

These ratios are impracticable for our experiments. In this connection, it is only necessary to call attention to the fact that the nozzle employed in the gas-oil experiments would have to have a diameter 10.3 times as large as in the kerosene experiments. We can, therefore, with our two liquids, produce no mechanically very similar phenomena and must content ourselves with an approximate comparison of the liquids with respect to the different forces individually, whereby the simultaneous effect of the other forces must be disregarded. This does not matter, in so far as it regards gravity, since the latter, on account of the high velocities of the liquid particles, can exert but a relatively small influence on them. On the other hand, it naturally would make a difference to disregard completely, on one occasion, the effect of the frictional forces and, on another occasion, the effect of the capillary forces, since both, acting simultaneously, must exert a very great influence on the processes in the jet. We have two liquids whose viscosity differs greatly, while their capillarity is almost exactly the same. We can, therefore, at least establish approximately similar mechanical phenomena, whether the effect of the viscosity or of the capillarity is the greater.

The frictional forces make it necessary, when $l_1 : l_2 = 1$ is chosen, that $c_1 : c_2 = 3.2$ and, when $c_1 : c_2 = 1$ is chosen, that $l_1 : l_2 = 3.2$. For the capillary forces, we must have $c_1 : c_2 = 1$, when $l_1 : l_2 = 1$, and conversely.

On considering the jet forms in the order of their occurrence with increasing pressure, we find that at first, with very small pressures and correspondingly small discharge velocities, the flow in the nozzle is laminar, but that it subsequently becomes turbulent at higher pressures. This phenomenon inside the nozzle is due to friction. The transition from the laminar to the turbulent flow takes place, according to Reynolds, at a velocity of $c = R\nu/l$. If the inside diameter of the nozzle, d = 0.53 mm, is substituted for l in the computation, then R is approximately 2000, an empirically-found number, which applies to fluid streams in smooth tubes (See Kohlrausch, "Praktische Physik," 1921, p. 249). The critical velocity was found to be 28 m/sec. for gas oil and 8.7 m/sec. for kerosene. The corresponding atomization pressures, without any special device for producing spiral motion, are 8.8 kg/cm² for gas-oil and 4 kg/cm² for kerosene. In the experiments without atomizer rods, it was found that, as soon as these pressures were reached (i.e., at the instant when the flow inside the nozzle became turbulent) the sickle-shaped phenomena and constrictions began to appear. In the experiments with atomizer rods, on the other hand, the sickles and

constrictions of the stream were found to begin at a lower pressure. In fact, the stronger the spiral motion, the lower the pressure. For gas oil the pressure varies from 4.5 kg/cm² down to 2 kg/cm²; for kerosene, from about 3 kg/cm² down to 2 kg/cm². The stream inside the nozzle is set in rotation by the spiral motion, whereby the peripheral velocity of the liquid particles increases inversely as their distance from the longitudinal axis of the nozzle. The velocity differences of neighboring liquid particles increase according to the size and direction of motion of the particles. It is obvious that turbulence thus begins sooner than in a stream where all the particles move in nearly the same direction. The Reynolds number, for a stream with a spiral motion, must therefore decrease as the latter increases. At the instant the flow in the nozzle becomes turbulent, the liquid particles are separated from the walls by vortices. This diminishes the resistance due to friction with relation to the increasing resistance of the eddies inside the stream and the velocity differences of neighboring particles suddenly diminish, which is recognizable in the rapid projection of the sickles from the mouth of the nozzle and their rapid increase in length for any further slight increase in pressure. So long as the flow is laminar, the particles on the surface of the jet have such a low velocity that the radial components of the latter, produced by the spiral motion, cause no visible change in the smooth cylindrical shape of the jet necessitated by the capillary force. Dur-

ing the beginning of the turbulence, however, the velocity of the particles on the surface of the stream increases rapidly, as likewise its radial components, thus causing the jet to widen. At this moment the rapidly increasing effect of the spiral motion, just under the nozzle orifice, is evident. So long, however, as the surface of the jet remains closed, as the result of its capillary force, the jet can spread only in one direction. In the other direction, it becomes all the thinner and the sickles and fan-shapes are formed. The capillary force also increases proportionally with the linear widening of the sickles. By the latter, the fluid particles which possess an outward motion are again deflected back toward the middle of the jet. Consequently the particles describe curves and come together again in a node. Their paths intersect and new sickles are formed. At the beginning of the phenomenon, i.e., so long as the jet closes again in a node under the last sickle, the surface of the sickle increases as the velocity of the jet increases. Since, with a strong spiral motion, the turbulence phenomena and sickles occur at lower discharge velocities and the sickles grow wider, the length of the sickles is considerably less in the discharge experiments with atomizers II and III.

Farther down on the jet, at the distance L_2 from the nozzle (Fig. 21,A), the outermost layers of liquid gradually begin to separate from the jet, by overcoming the capillary

force, and break up into drops. This phenomenon is caused by the friction of the air and takes place, at the different velocities of the jet, approximately according to the law of mechanical similitude, i.e., as the pressure and velocity increase, the separation point moves upward and L_2 becomes shorter. For gas oil, flowing without spiral motion, we find, when L_2 and the corresponding discharge velocity are introduced into the Reynolds formula at a pressure increase of 6-10 kg cm², that the closed jet begins to break up at a number $R \sim 1,500,000$ down to 1,200,000. With increasing discharge velocity, the number R decreases somewhat, but if, on the other hand, the constant for the formula of the capillary force is determined, values are obtained which increase from about 6,600,000 to 8,300,000. It follows, therefore, that both capillary and frictional forces aid in causing the phenomenon.

If we compare the formation of similar sickles and constrictions for gas oil and kerosene, we note, in the discharge without spiral motion, that the velocity ratios for like lengths are the largest at the beginning of the phenomena and decrease with increasing length of the individual sickles and the corresponding decrease in their number. If we use the index 1 for gas oil and 2 for kerosene, we have:

For 3 sickles of about 60 mm total length,

$p_1 = 11 \text{ kg/cm}^2 \quad p_2 = 4\frac{1}{2}\text{–}5 \text{ kg/cm}^2 \quad c_1 : c_2 \sim 2.6$

For 2 sickles of about 60 mm total length,

$p_1 = 12 \text{ kg/cm}^2 \quad p_2 = 5\frac{1}{2} \text{ kg/cm}^2 \quad c_1 : c_2 \sim 2.0$

For 1 sickle of about 60 mm length,

$p_1 = 13 \text{ kg/cm}^2 \quad p_2 \ 8 \text{ kg/cm}^2 \quad c_1 : c_2 \sim 1.4$

If only frictional forces were present, the length-ratio constant would be 3.2, while if only capillary forces were acting, it would be 1. From the decrease in the length ratio, we may therefore conclude that the effect of the frictional force has much to do with the formation of the sickles, but that it decreases to the same degree as the effect of the capillary force increases with the increasing size of the individual sickles. If the discharge takes place with a spiral motion, the length of the sickles is considerably less and it is no longer possible to obtain sickles of the same length and number with both experimental liquids.

The further course of the transition from laminar to turbulent flow is characterized by the fact that, after the total length of the sickles has reached its maximum, the lowest constrictions begin to change into an atomization cone. After the dissolution of the last node, there remains an oil spray which has the shape, due to the spiral motion, of an opening fan, whose length L (Fig. 21, G and H) rapidly diminishes and whose lower edge breaks up into drops. The decrease of L, with the increase in the discharge velocity, indicates that a mechanical similarity of the processes of flow is again being established in connection with further velocity increases. After the oil spray has become very short, it rolls together

into a cone, under the influence of the spiral motion. If we compare the two experimental liquids, when they have the same conical shape and the same length of the oil spray (round conical shape, like Fig. 21, J or K, length of oil spray $L = 2$ to 3 mm) with reference to the discharge velocities, we obtain

1. For nozzle without atomizer,

   $p_1 = 17$ kg/cm² $c_1 = 45$ m/sec
   $p_2 = 11$ " $c_2 = 35.5$ m/sec. $c_1 : c_2 \sim 1.3$

2. For nozzle with old atomizer,

   $p_1 = 13$ kg/cm² $c_1 = 35.5$ m/sec.
   $p_2 = 5\text{-}6$ " $c_2 = 17.0$ " $c_1 : c_2 \sim 2.1$

3. For nozzle with atomizer II,

   $p_1 = 9$ kg/cm² $c_1 = 22.5$ m/sec.
   $p_2 = 5$ " $c_2 = 10.5$ " $c_1 : c_2 \sim 2.2$

4. For nozzle with atomizer III,

   $p_1 = 7\frac{1}{2}$ kg/cm² $c_1 = 18.5$ m/sec.
   $p_2 = 4\frac{1}{2}$ " $c_2 = 8$ " $c_1 : c_2 \sim 2.3$.

The stronger the spiral motion, the more important the influence of the frictional force becomes, with the production of similar jet shapes to be judged according to the velocity ratio of the latter. If the discharge of both liquids occurs without the spiral motion, or with equally strong spiral motions, the phenomena connected with the formation of the atomization cone, with increasing velocity, apparently depend increasingly

on the effect of the capillary force, when we introduce into the comparison the velocity ratios previously found for similar sickle formations.

After the transition from laminar to turbulent flow is completed, then, as in laminar flow, a recurrence of the mechanical similarity of the flow phenomena, at different velocities for one and the same liquid, is to be expected. In the breaking up of the oil spray into drops, in case only capillary forces were present, the drop diameters would have to decrease, according to the law of capillarity, inversely as the square of the velocity. The formulas, derived from the experimental results (pages 6, 7 and 8) prove, however, that the decrease in the drop diameter takes place only in the inverse ratio to $\sqrt[n]{c}$ and hence in a much less degree than one would suppose. The reason for this is to be sought in the other forces acting in the jet simultaneously with the capillary force. In the discharge without the spiral motion, we obtain, for the same sized drops of gas oil and kerosene, the following velocity ratios:

Drop diameter = 0.2 mm,	$c_1 : c_2 =$ 8.3 m/sec.	: 3.3 m/sec.	~2.5
" " = 0.1 "	$c_1 : c_2 =$ 38 "	: 19 "	~2.0
" " = 0.05 "	$c_1 : c_2 =$ 178 "	: 107 "	~1.7

Therefore it is necessary to determine, with increasing velocity, a transition from the constant which fixes a value for the exclusive effect of friction forces to the corresponding number for the capillary forces.

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under what conditions an oil spray breaks up into drops. In further experiments, the relations should be so fashioned as to enable the formulation of a theory on the basis of the law of mechanical similitude. The experiments should therefore, be comparative and employ mechanically similar processes. For example, parallel experiments to the above might be undertaken with two liquids differing as greatly as possible in capillarity, while having the same viscosity.

The main object of this investigation was to determine the size of the drops in mechanical atomization. Should it, however, prove to be an incentive for further attempts to solve the problem of atomization, it would be a very gratifying result.

Translation by Dwight M. Miner,
National Advisory Committee
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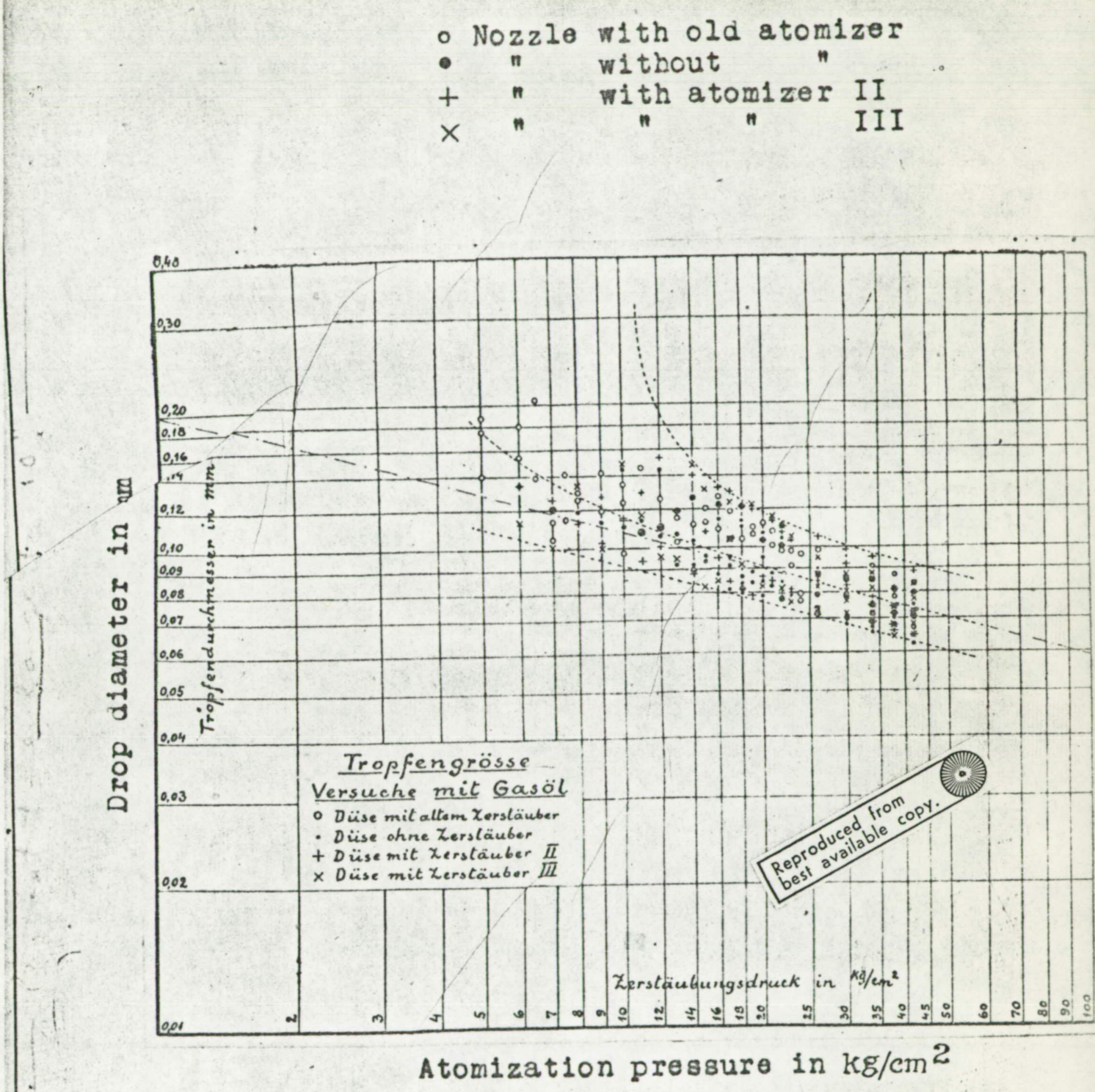


Fig.24 Experiments with gas-oil.
Size of drops plotted against
the atomization pressure.

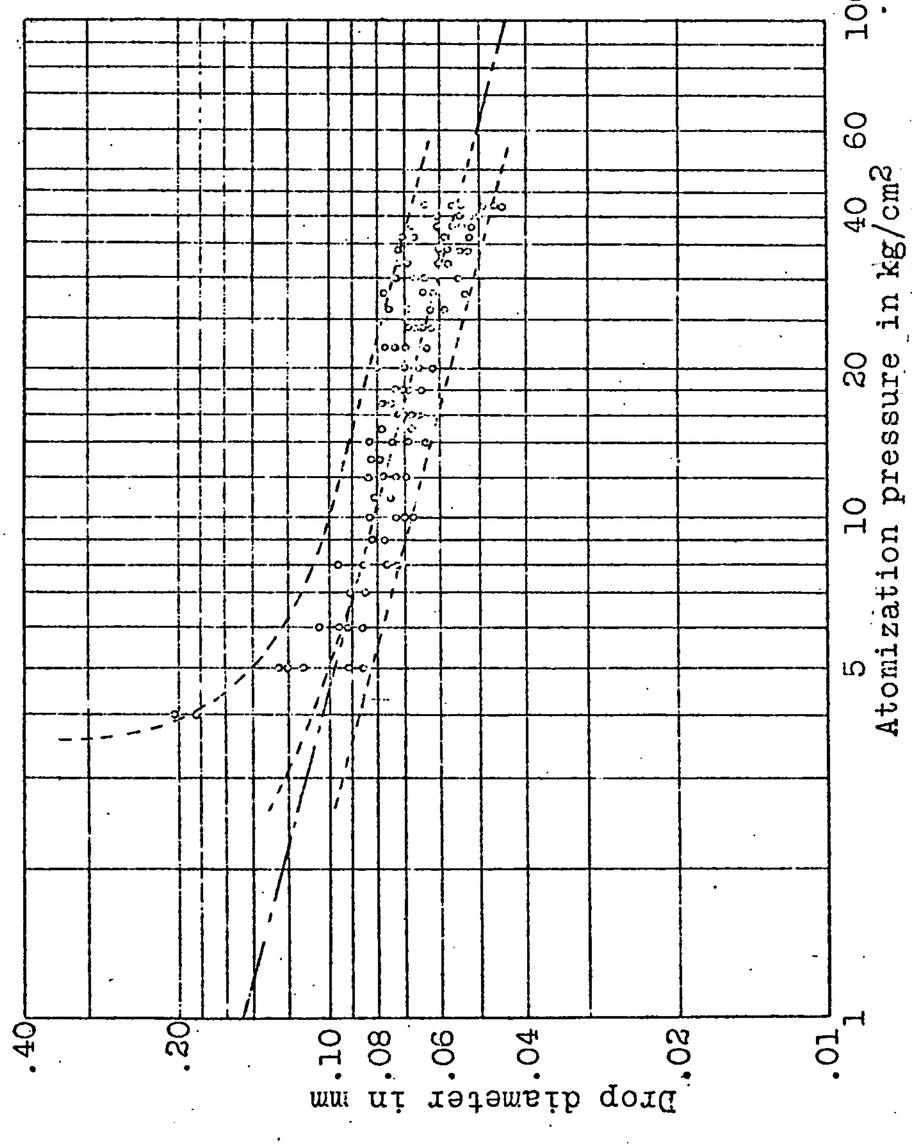


Fig.25 Experiments with kerosene. Size of drops. Nozzle with old atomizer. Size of kerosene drops plotted against the atomization pressure.

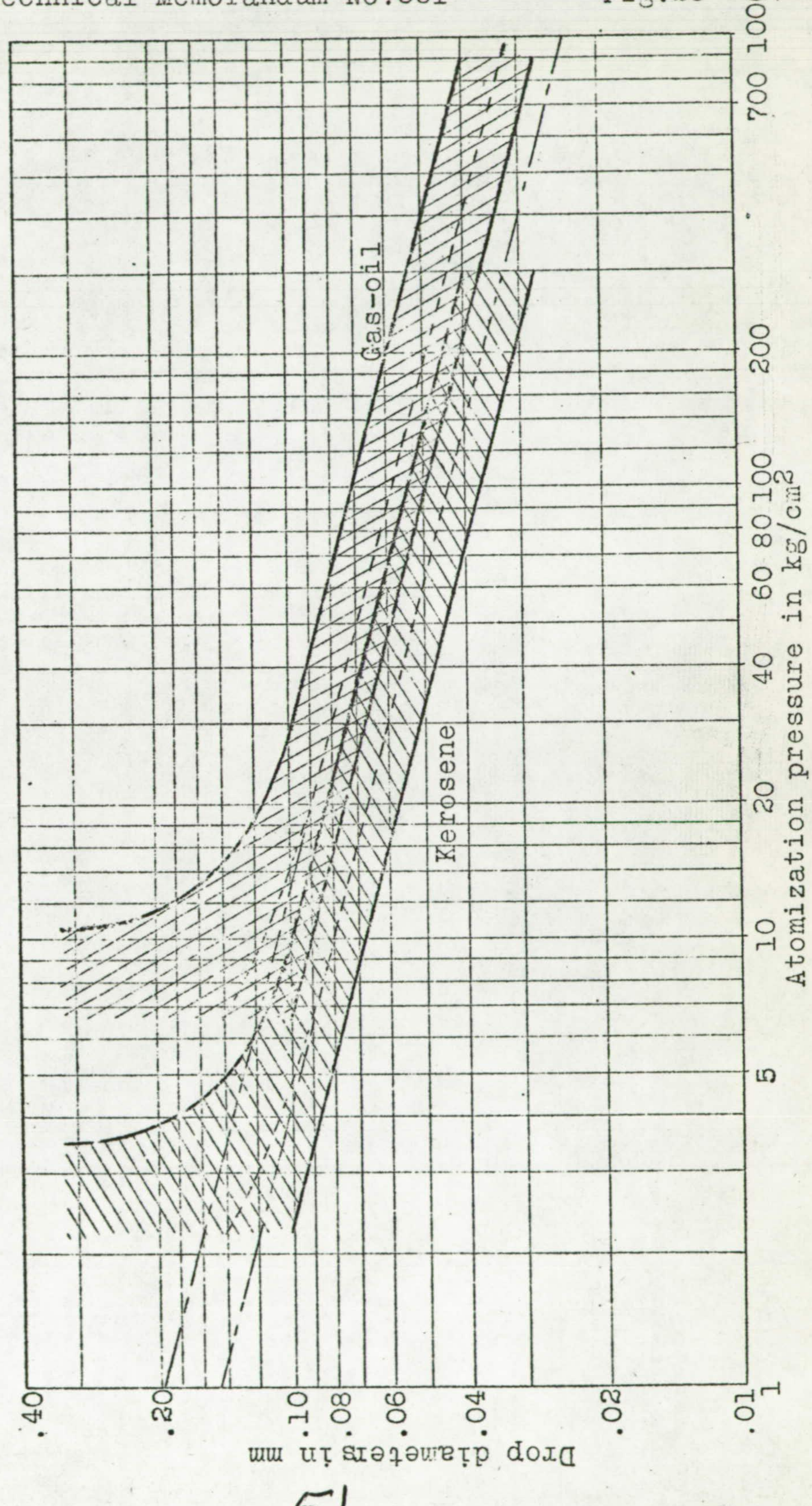


Fig.26 Zones of size of drops of gas-oil and kerosene plotted against the atomization pressure.

51

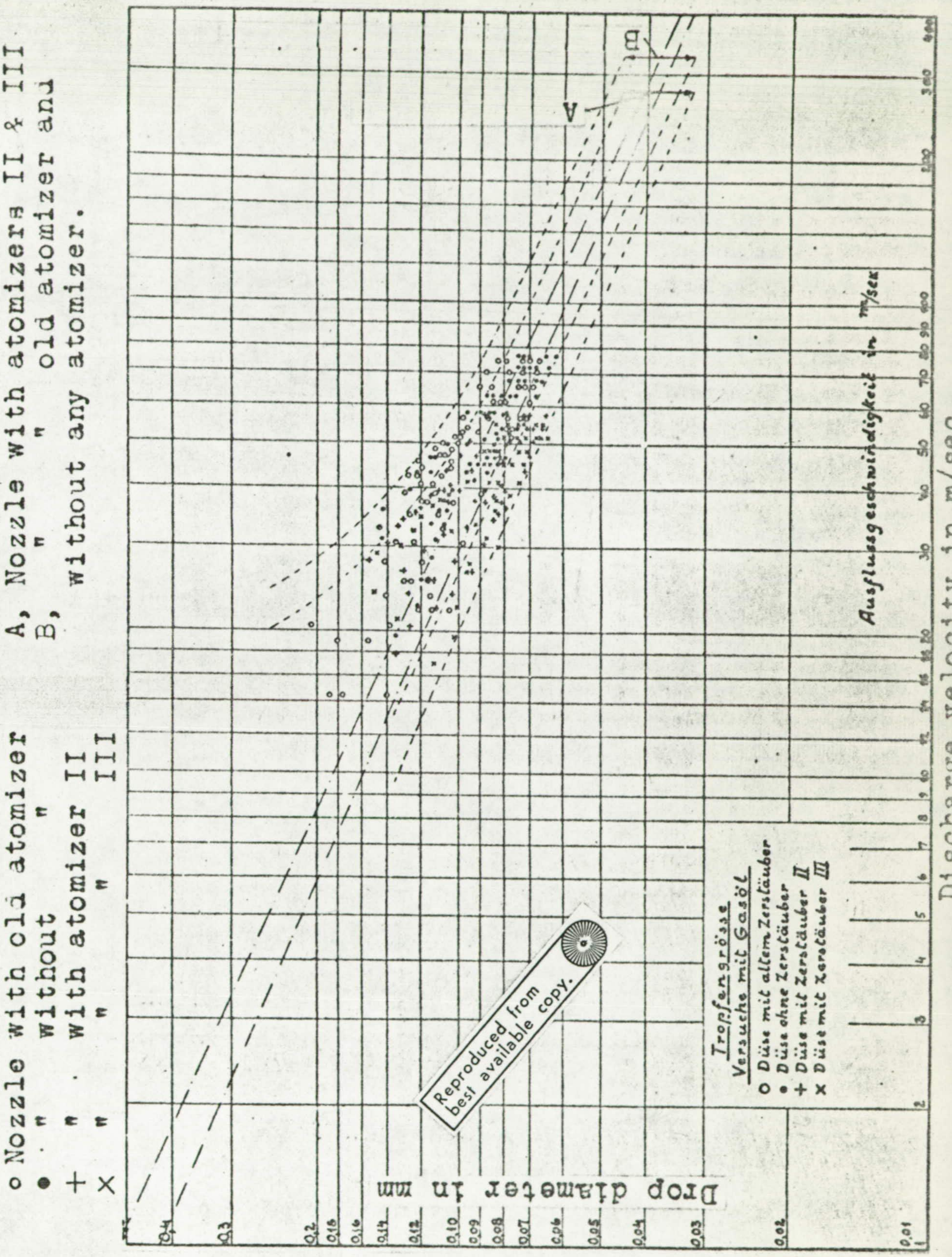


Fig.27 Experiments with gas-oil. Size of drops plotted against the discharge velocity.

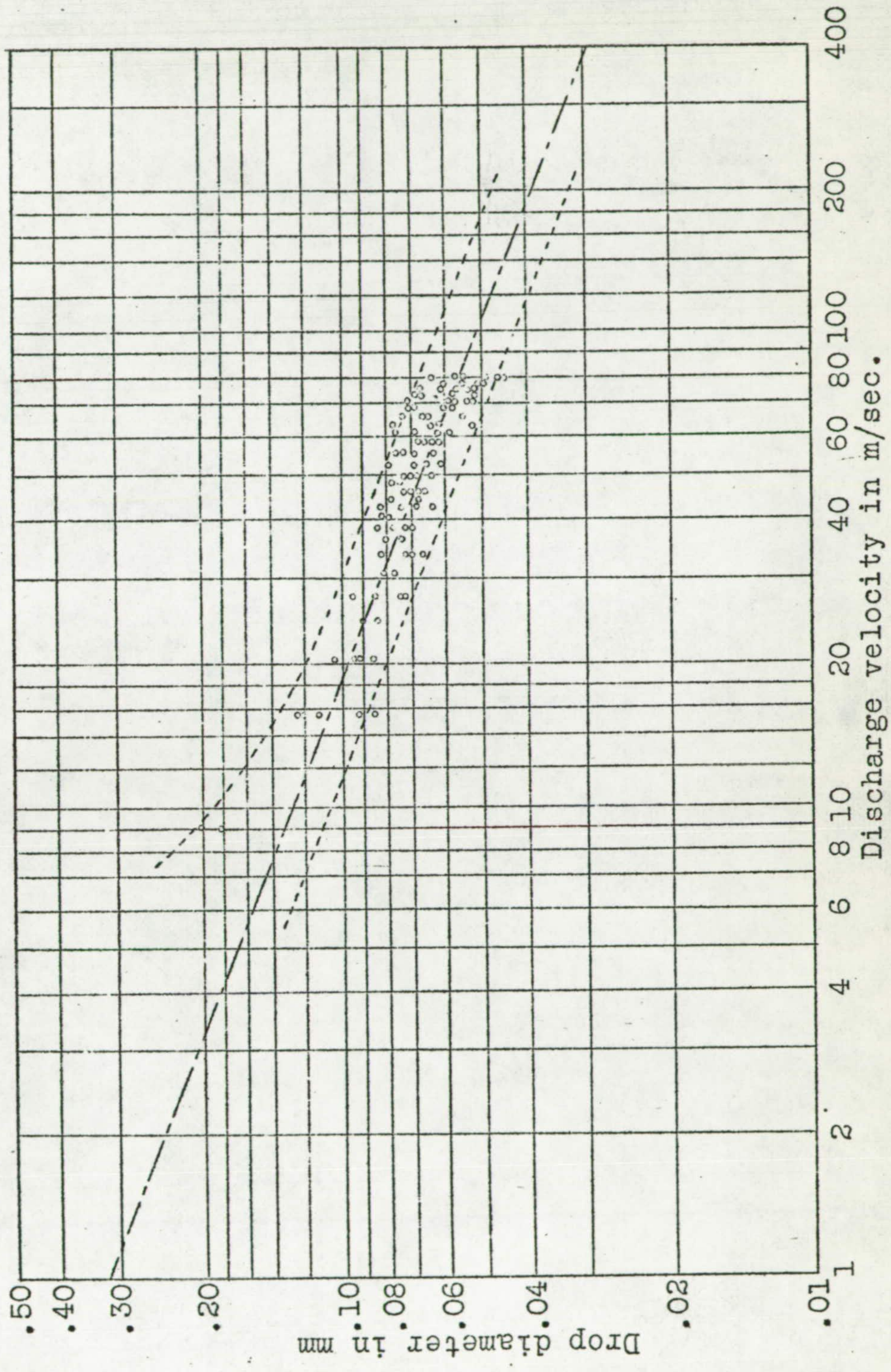


Fig.28 Experiments with kerosene. Size of drops. Nozzle with old atomizer. Size of drops plotted against discharge velocity.

A, Gas-oil. Nozzle with old atomizer or without.
B, " " atomizers II or III.
C, Kerosene " old atomizer.

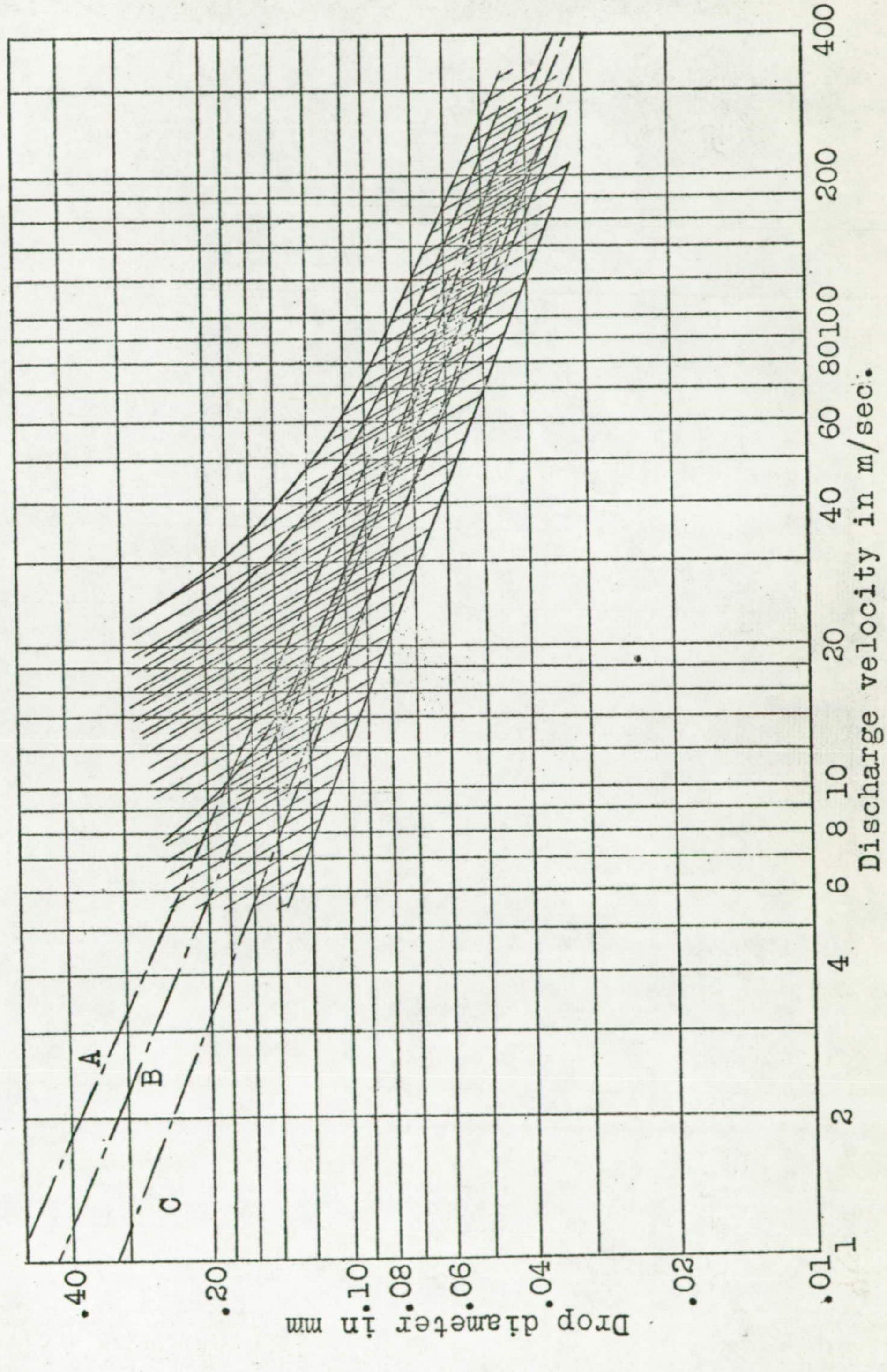
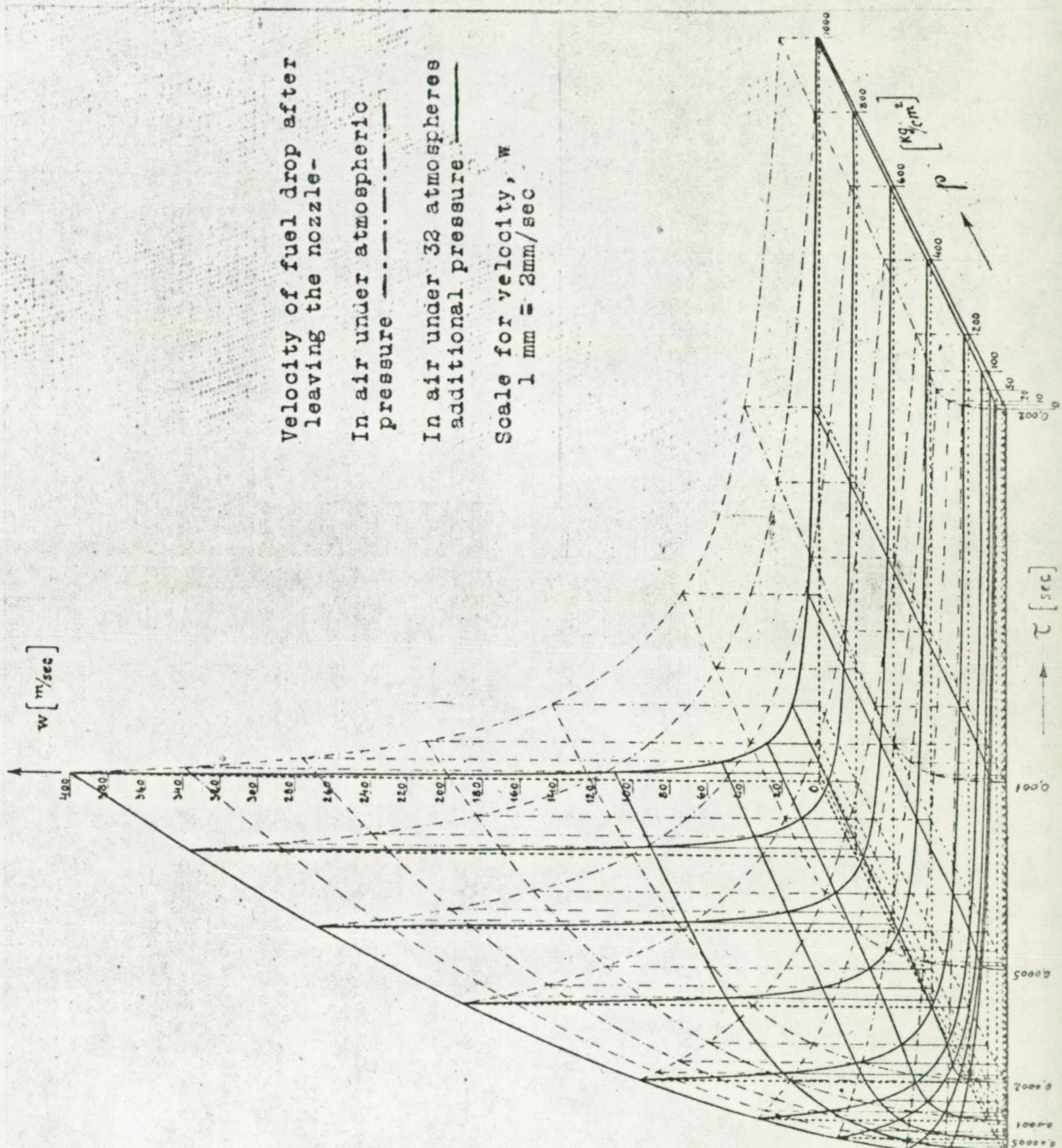


Fig.29 Zones of the size of drops of gas-oil and kerosene plotted against discharge velocity.


Velocity of fuel drop after leaving the nozzle-
In air under atmospheric pressure
In air under 32 atmospheres additional pressure
Scale for velocity, w 1 mm = 2mm/sec
w [m/sec]
p [kg/cm²]
τ [sec]

55

Fig. 30

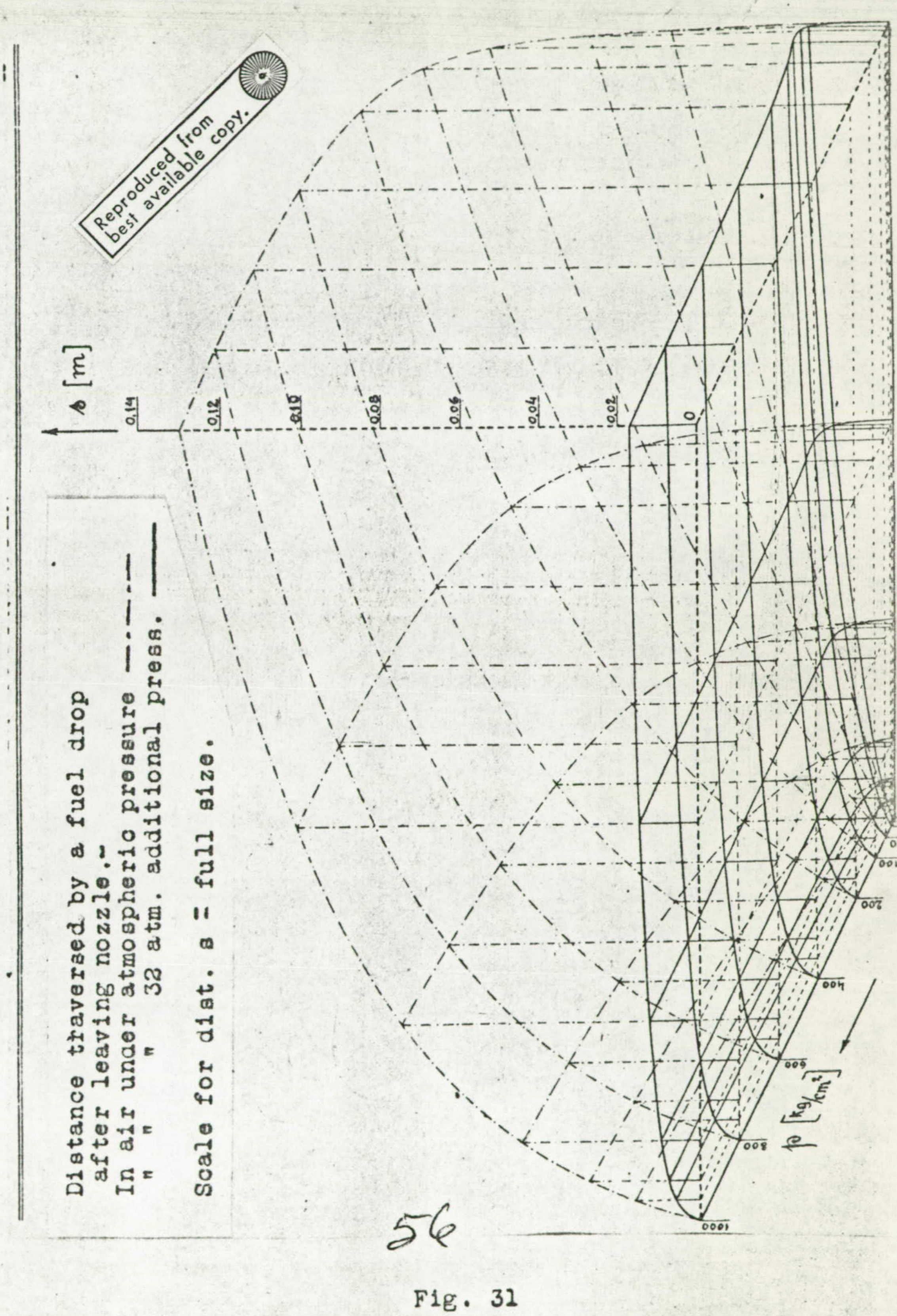

Distance traversed by a fuel drop after leaving nozzle.-
In air under atmospheric pressure ——.——
" " 32 atm. additional press. ———
Scale for dist. s = full size.
s [m]
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0
τ [sec]
0.002
0.001
0.0005
0.0002
0.0001
0.00005
p [kg/cm²]
1000
800
600
400
200
100
50
10
0

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Fig. 31